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DEPOSITION OF THERMAL ENERGY BY NUCLEAR EXPLOSIVES

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Contract No. W-7405-eng-48

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April 6, 1964

Presented at the Third Plowshare Symposium,
April 21-23, 1964, University of California, Davis.

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ABSTRACT

A fraction of the energy released by the underground detonation of nuclear explosives is locally deposited as residual thermal energy. An accurate prediction of this usable fraction of the energy released is necessary to evaluate the feasibility of several of the proposed projects in the Plowshare Program.

Analysis of dynamic temperature distribution data derived from experimental measurements in three different geological media — tuff, granodiorite, and salt — indicates that the distribution of residual thermal energy several months after detonation may be deduced from currently available computer-code predictions of the energy distribution at very early times.

However, the actual fraction of energy remaining is strongly dependent on the degree of containment achieved during the nuclear detonation.

In addition, the thermodynamic quality of the residual heat energy is directly a function of the total water content of the medium in which the detonation takes place.

INTRODUCTION

The Plowshare Program was established in 1957 by the Atomic Energy Commission to investigate and develop industrial and scientific uses of nuclear explosives. Several large-scale chemical engineering proposals have been made to utilize the energy deposited by nuclear explosives. Grebe et al.[1] have suggested the concept of an underground "retort" where the high

*Work performed under the auspices of the U. S. Atomic Energy Commission.

temperatures and pressures associated with a nuclear detonation could carry out a variety of chemical syntheses. Indeed, one of the objectives of Project Gnome[2] was to investigate the problems of recovery of heat from the post-detonation environment in a salt medium. The use of nuclear explosives to assist in recovery of petroleum products from tar sands has been studied in great detail.[3] Similar studies on oil shales are available.[4] Teller[5] has suggested the possible use of nuclear explosives to aid lunar expeditions in developing a lunar water supply. Higgins et al.[6] have studied the general problem of induced chemical reactions with nuclear explosives.

Evaluation of these proposals requires a detailed analysis of the energy deposition from an underground nuclear detonation. Electronic computer codes[7,8] have been developed which provide the required energy deposition analysis at early times. Because of the complexity of the partial differential equations used in the codes and experimental uncertainties in the input data relating to transitions between gaseous, liquid, plastic, fractured and elastic states, experimental verification of the mathematical predictions would be reassuring.

This paper will present a summary of the available data on residual thermal energy from nuclear detonations in three different geological media: tuff, halite, and granodiorite.

ENERGY DEPOSITION MECHANISMS

The fraction of energy deposited by an underground nuclear detonation is dependent on the degree of containment achieved. In order to better define containment, we look at a plot of the cavity radius and shock front position as a function of time. (See Fig. 1.)

Above the shot the shock front travels vertically until it reaches the surface where it is refracted downward again. Containment is achieved if the internal cavity pressure is equal to or less than overburden or lithostatic pressure at the time this reflected wave reaches the cavity wall.

This containment concept is based on the model that energy released by the nuclear detonation vaporizes the nuclear explosive materials, forming a rapidly enlarging fireball.[7]

As the shockwave passes radially from the point of detonation, its strength decreases rapidly. Thus, the energy density falls rapidly so that the temperature to which the surrounding medium is heated decreases.

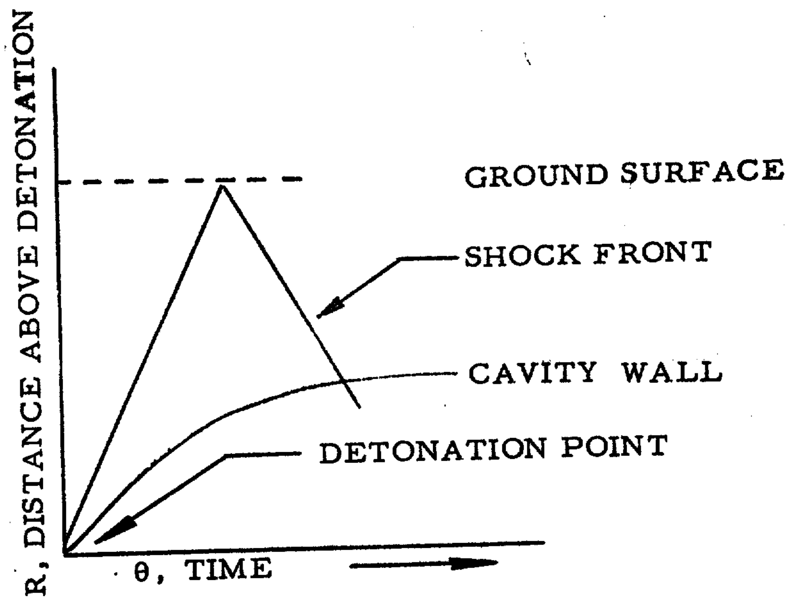

Fig. 1. Cavity radius and shock front position as a function of time.

This is shown in Fig. 2; the percentage of the total nuclear energy available as residual heat is shown as a function of the minimum temperature rise produced.

This temperature distribution is calculated for very early times. The time required for the cavity to grow, referred to as the hydrodynamic phase, is of the order of 100 milliseconds. The distribution shown in Fig. 2 was calculated at the end of the hydrodynamic phase.[6] As the cavity region cools, the distribution of energy shifts such that the fraction originally at higher temperature flows into lower temperature regions, producing a distribution similar to the dashed curve, Fig. 2.

Energy Loss Mechanisms

At the end of the hydrodynamic phase, the molten rock flows to the cavity bottom, and thermal stress and decrepitation spall wall material into the cavity. Within usually a few seconds to minutes, the massive chimney collapse occurs.

The principal heat loss mechanisms that occur at late times are: (1) conduction through the fractured zone surrounding the bottom half of the cavity; (2) conduction into the shattered chimney material; and (3) gas phase convective loss into the chimney material. A refluxing zone is set up within

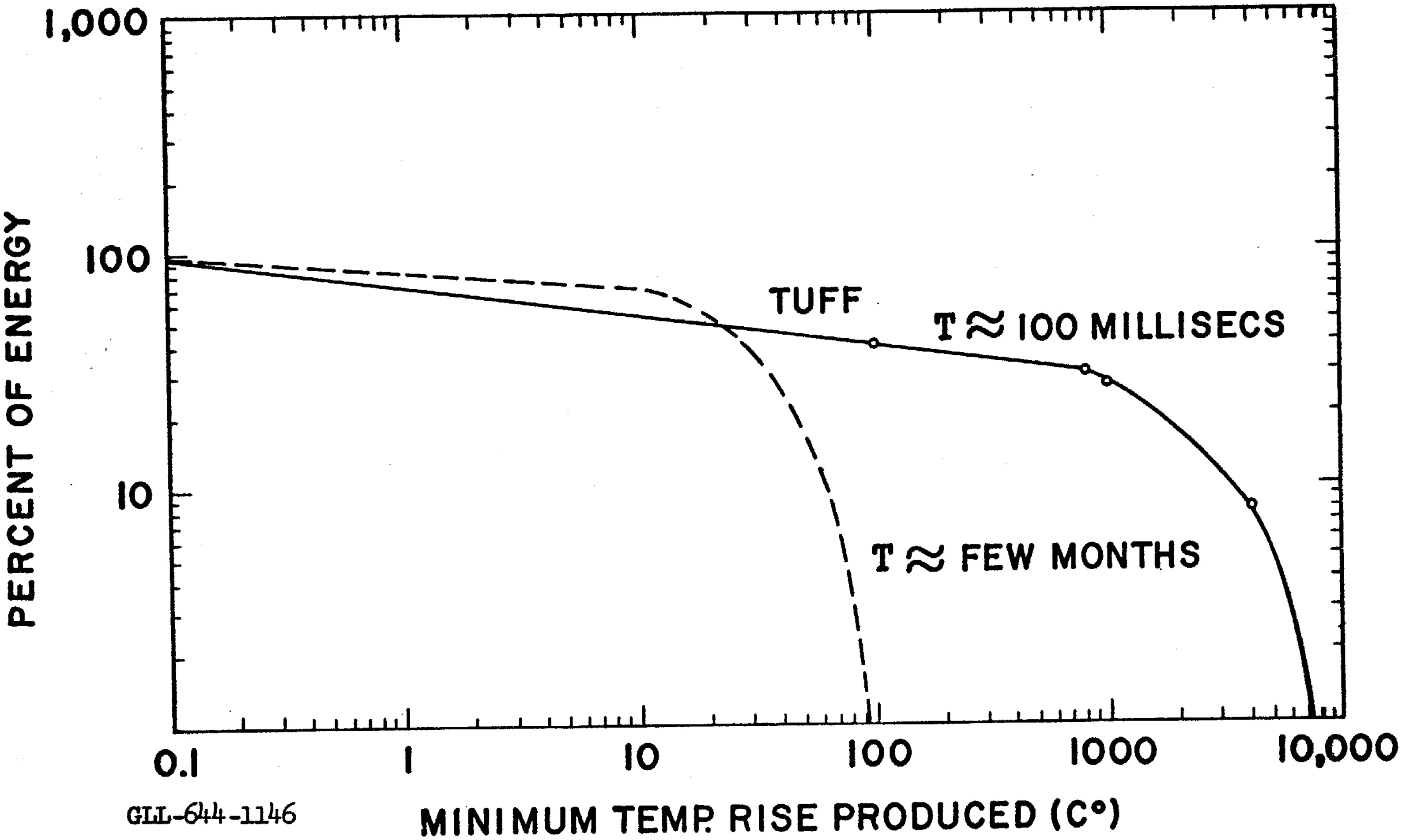

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Fig. 2. Calculated minimum temperature rise produced (tuff).

the chimney region proper with water acting as the refluxing agent. At very late times (several months), liquid water will exist in the lower chimney regions so that liquid phase convection will play a minor role.

Because of the complexities involved in the heat transfer calculations, no precise techniques exist for analytical solution of the problem. No three-dimensional unsteady state heat transfer computer codes exist at the present time. Since the energy distribution calculated by the existing computer codes[7,8] is given only at the end of the hydrodynamic phase of cavity growth, and no analytical methods exist for predicting the dynamic character of the energy loss mechanisms for the time period from a few minutes to a few months, an experimental approach must be used. Therefore an attempt is made in this paper to analyze the existing data relating to the general problem of residual thermal energy from underground nuclear explosions.

Residual Energy Calculations

Because of the great expense involved in drilling suitable holes through postdetonation environments, temperature data have been obtained only from holes that were drilled primarily to obtain radiochemical samples. Thus, in a number of the events studied, the amount of temperature data available is sparse and its location within the postdetonation environment is not optimum. For example, a very complete system of holes was drilled through the lower hemisphere of the Rainier event[7,10] but no data are available on temperature distributions within the chimney region where an appreciable fraction of the device energy remains. In the case of the Shoal event,[11] only a single vertical hole was drilled. No horizontal holes are planned to be drilled in the lower hemisphere within the time that high temperatures in this region would still exist.

Table I summarizes pertinent data on the events used in this paper.

Temperature profiles deduced for the various events in this report are shown in Figs. 3 through 8.[10,13,16]

The volume of material included within the given isotherm was estimated by graphical integration techniques using the theorem of Pappus.[14] Physical properties are listed in Table II.[15]

Specific heat data were obtained from Birch.[9]

Table I. Data summary.

Event	Detonation date	Yield(W) (kt)	Medium	Vertical burial depth (D) (feet)	Calculated fraction of thermal energy residual	Max temp observed (°C)	Elapsed time before temp measurements (months)
Neptune	10/14/58	0.115	tuff	99	--	20.5	6
Blanca	10/30/58	19	tuff	835	0.0692	50	4
Logan	10/16/58	5.0	tuff	830	0.228	85	6
Rainier	9/19/57	1.7	tuff	790	0.2295	90	5
Tamalpais	10/8/58	0.072	tuff	330	--	53	3
Gnome	12/10/61	3.0	salt	1184	0.95	83	6.5
Hardhat	2/15/62	4.5	granodiorite	939	0.410	88	11
Shoal	10/26/63	12.5	granodiorite	1205	1.0685	599	2.5

Table II. Some typical properties of four rock types.

Physical Properties	Granodiorite	Salt	Tuff
Bulk density (natural state)	2.67[a]	2.2[b]	1.85[c]
Bulk density (dry)	2.67[a]	2.18[b]	1.6[c]
Grain density	2.69[a]	2.25[b]	2.35[c]
Porosity	0.9%	3%	32%
Total water content (by wt)	0.9%	1%	20%

[a]Skrove, J. W., Lawrence Radiation Laboratory, Livermore, private communication.

[b]U. S. G. S., 1962.

[c]Diment, et al., 1959.

The energy content contained within each isotherm is given by:

$$Q = 28317\ (\rho V)\ (C_p \cdot 10^7)\Delta T$$

where
V = volume, ft^3
ρ = media density, g/cc
C_p = joules/g, °C
ΔT = average temperature rise above ambient, °C
Q = energy content in ergs.

The energy released by 1 kiloton of nuclear yield is equivalent to 4.185×10^{19} ergs or 10^{12} calories.

Figure 9 summarizes the energy distribution data for the detonations that were conducted in tuff media. Only the data for Rainier, Logan, and Blanca are plotted since but one drill hole each was completed for the Neptune and Tamalpais events. A meaningful temperature profile could not be constructed due to the location of the single drill hole. The Rainier event (Fig. 10) is known to have contained completely. Postshot exploration of the Logan site indicated penetration of the preshot drift by the expanding cavity. The asymmetries in the deduced Logan temperature profile clearly indicated that such penetration did indeed occur. The Blanca event cratered to the surface (see Fig. 11). The asymmetry in the Blanca temperature profile is probably due to the chimney collapse mechanism, since the chimney broke through a steep slope rather than a level plane as is the case in alluvial shots. Comparison of the curves which show percent of energy vs minimum

Vertical section

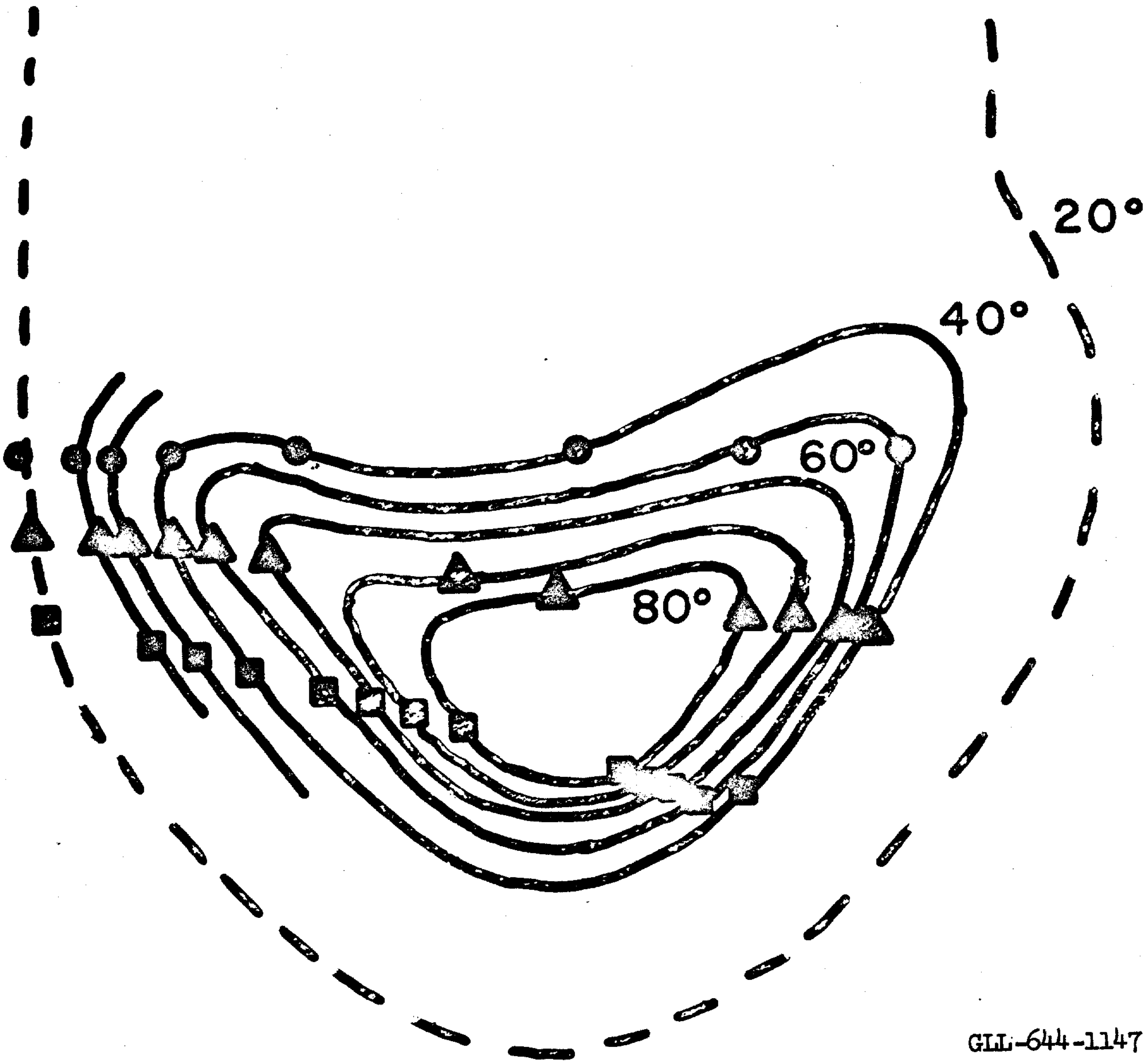

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Fig. 3. Rainier temperature profile.

Grafted

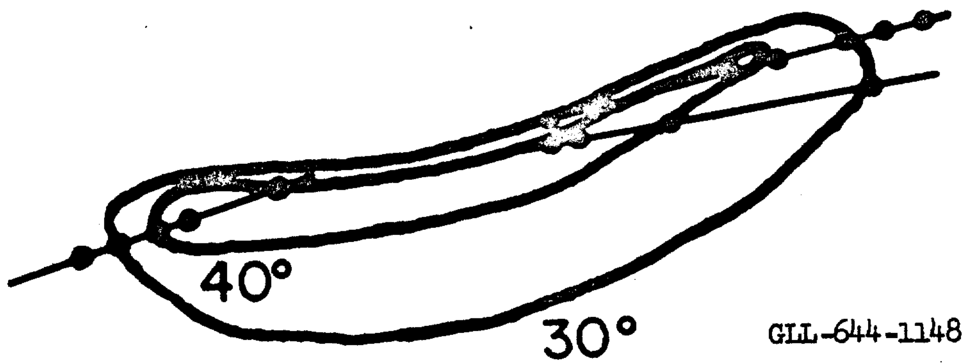

Fig. 4. Blanca temperature profile.

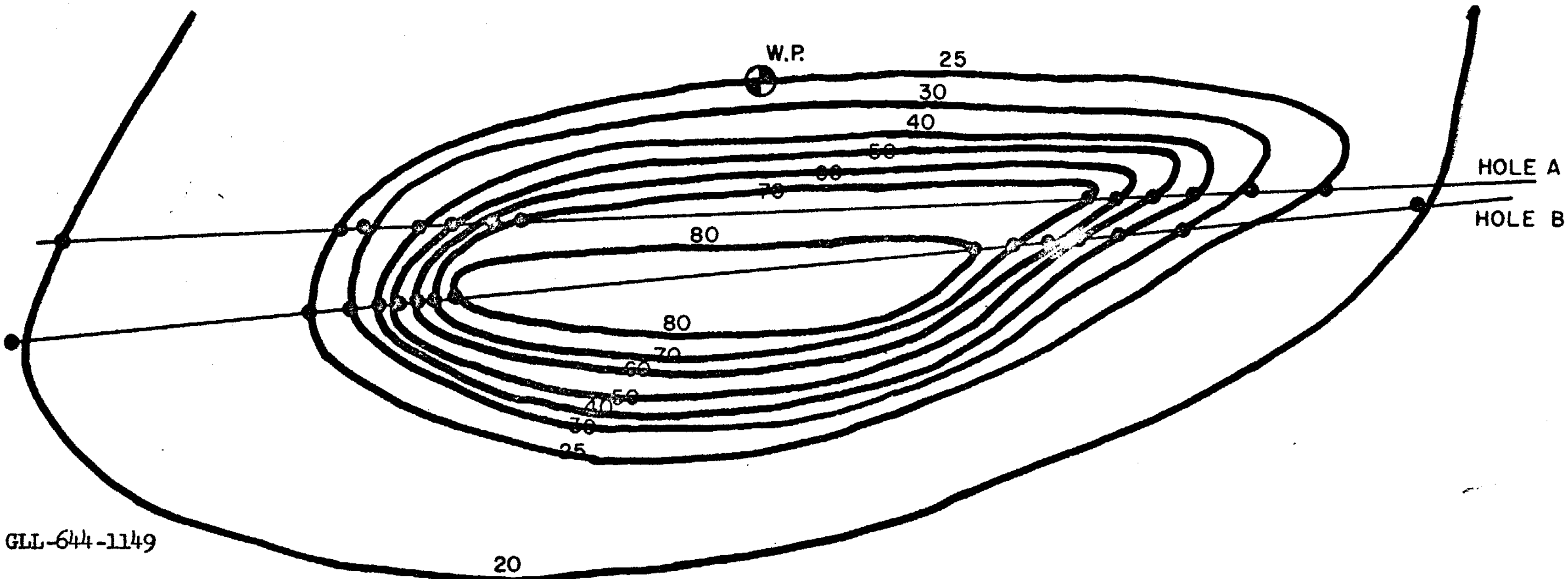

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Fig. 5. Logan temperature profile.

Extended into tunnel

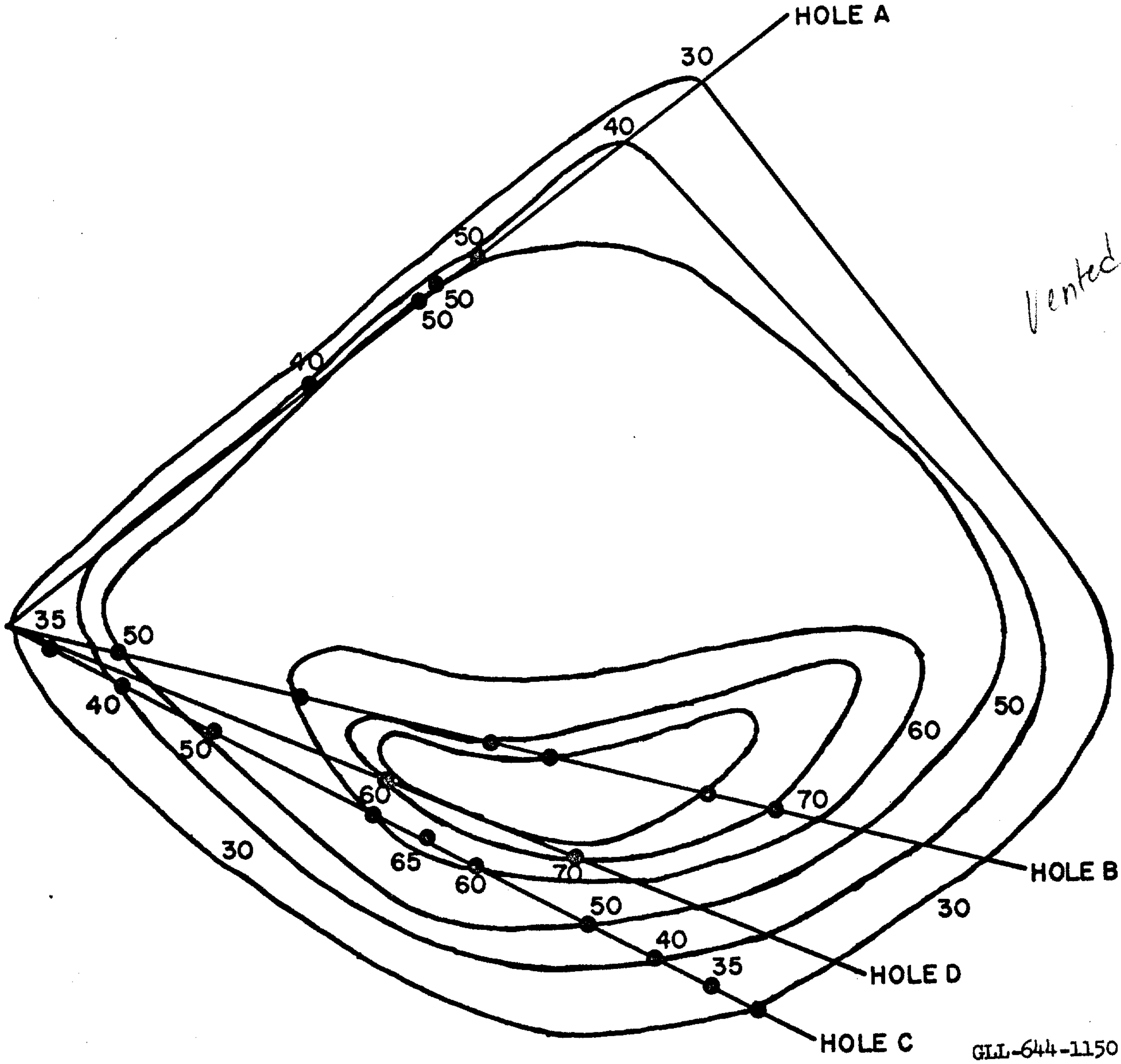

Fig. 6. Gnome temperature profile.

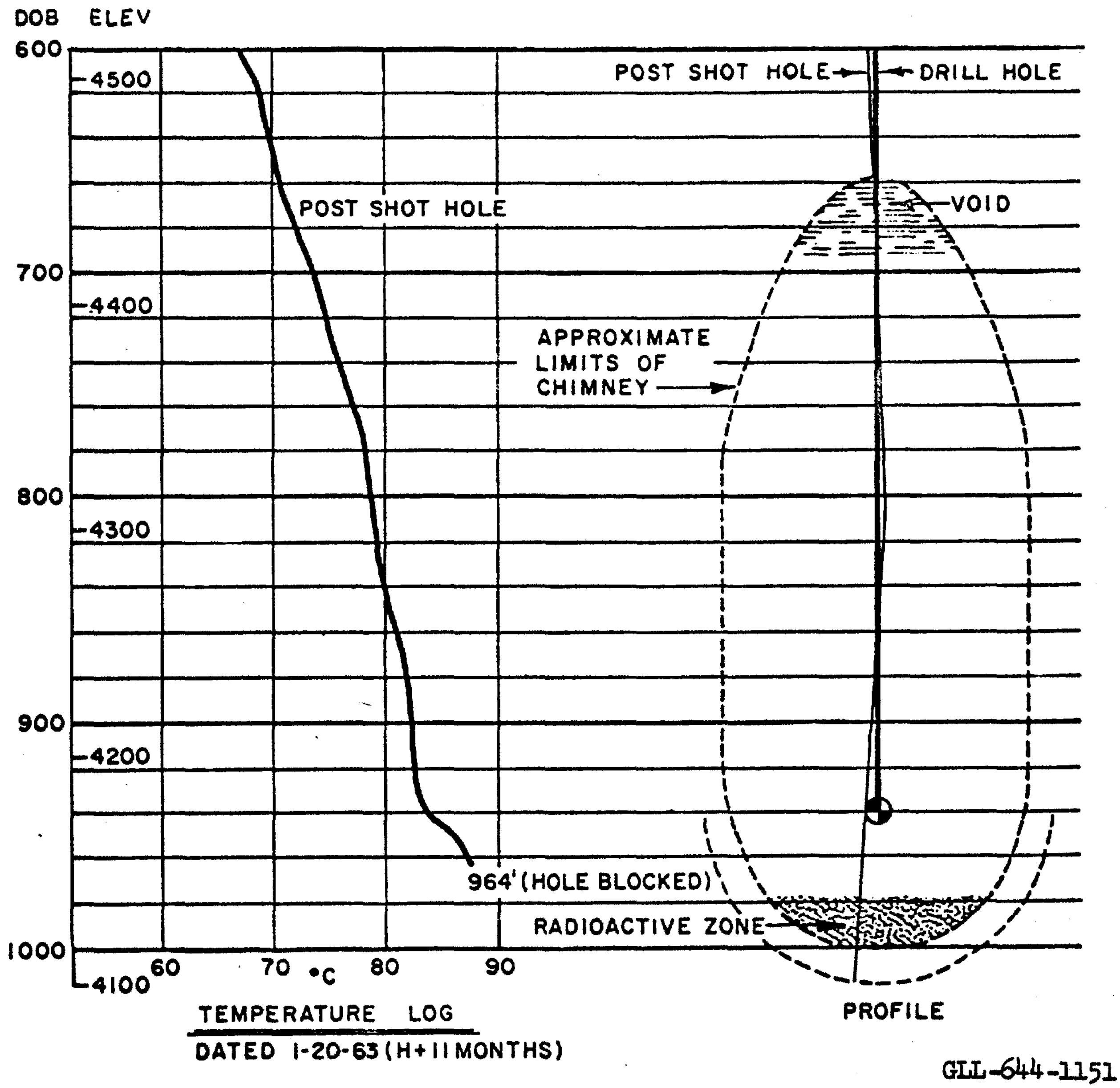

Fig. 7. Hardhat temperature profile.

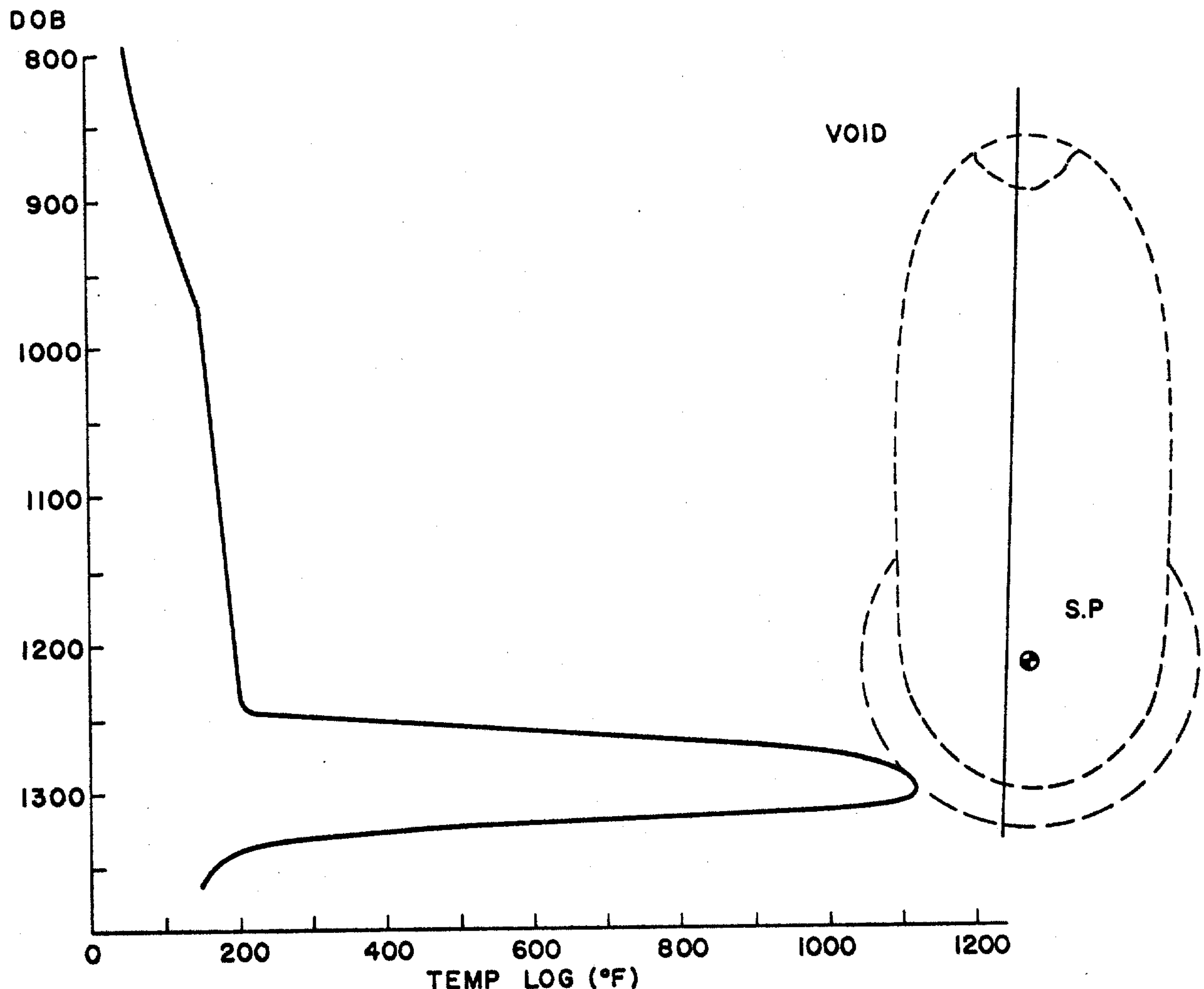

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Fig. 8. Shoal temperature profile.

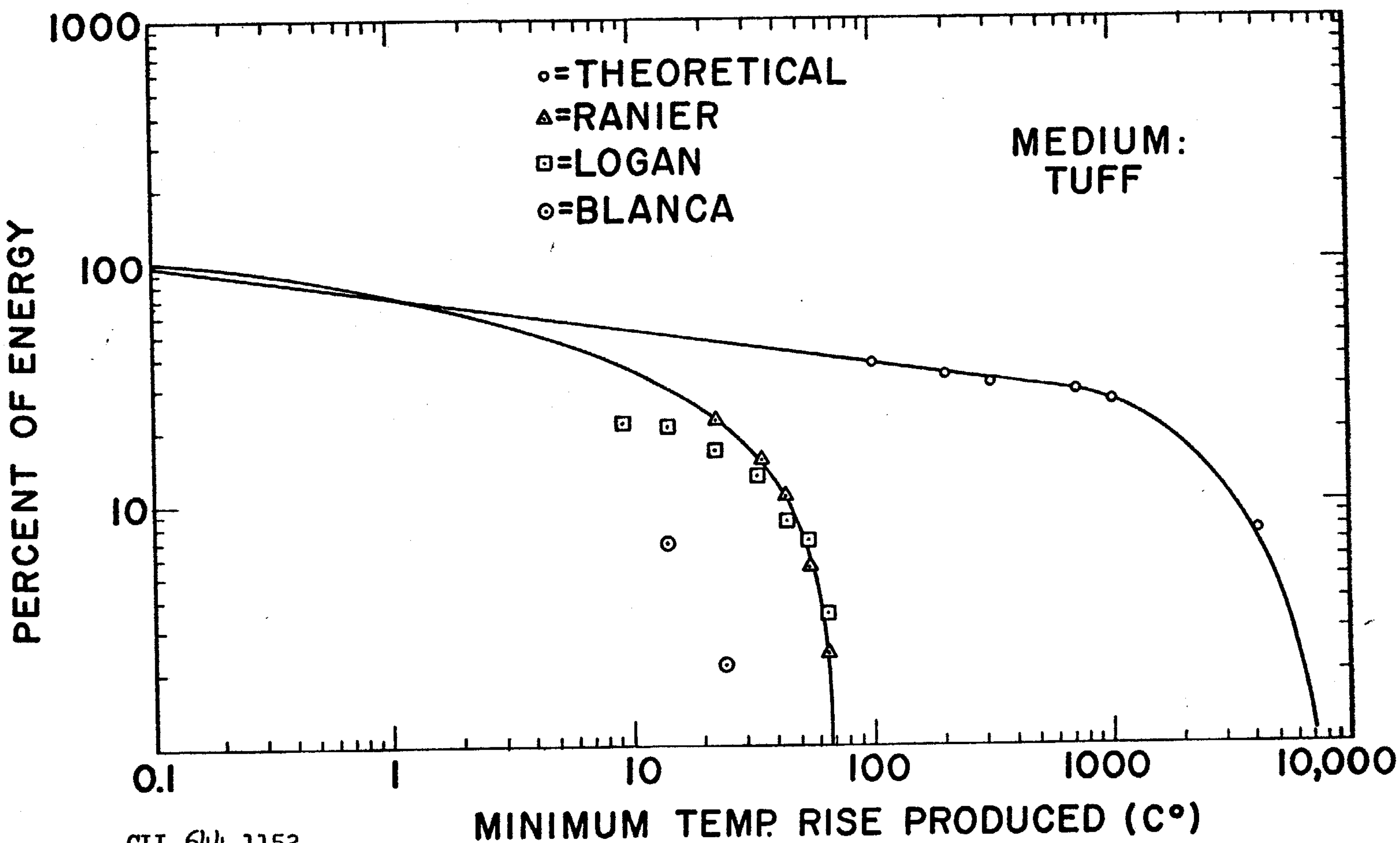

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Fig. 9. Observed minimum temperature rise produced (tuff).

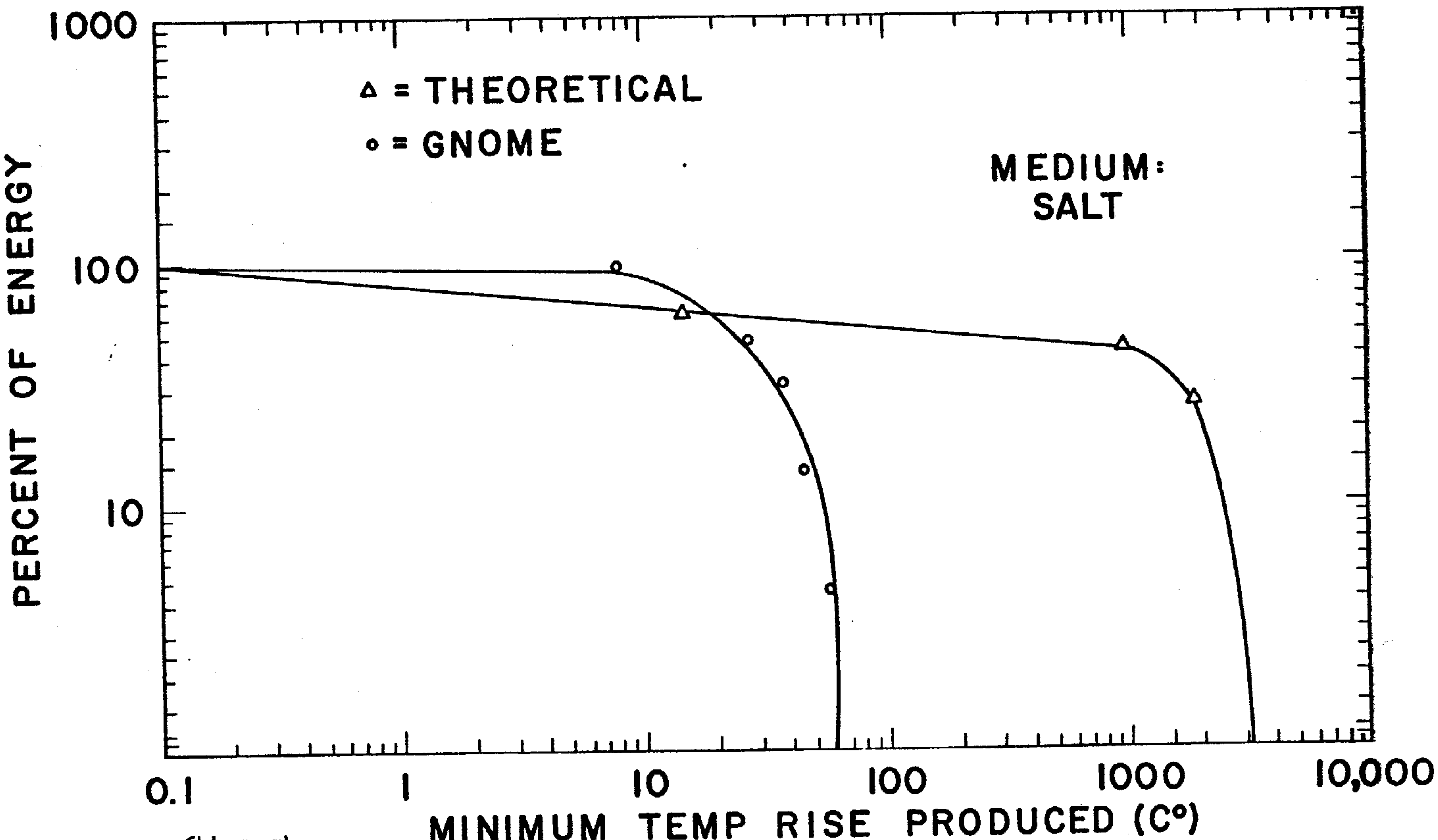

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Fig. 10. Observed minimum temperature rise produced (salt).

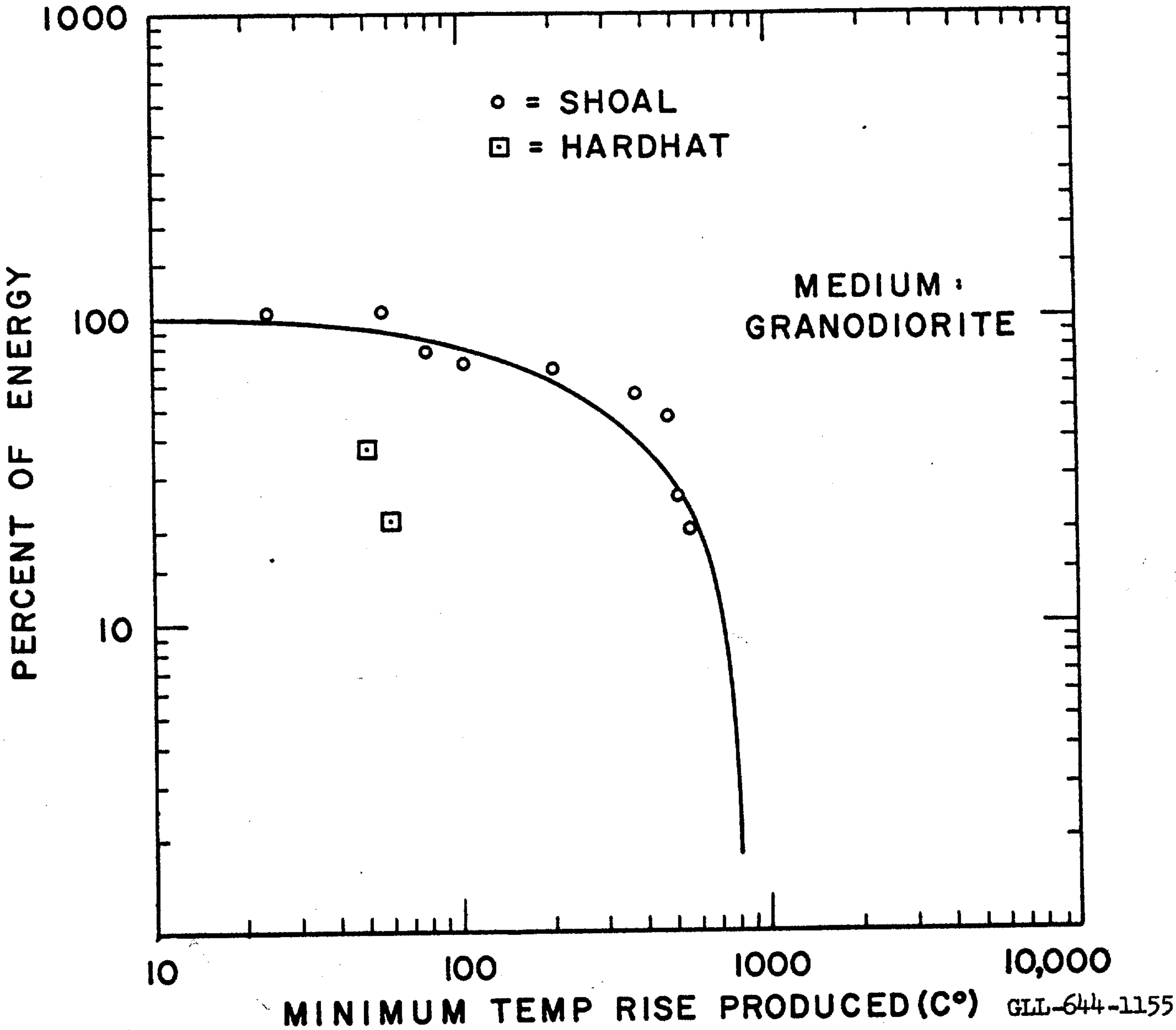

Fig. 11. Observed minimum temperature rise produced (granodiorite).

temperature rise produced clearly indicate the effect of containment on the percent of residual energy. In the case of Blanca, where effectively little containment was achieved, the fraction of residual energy remaining is very low. The maximum temperature observed is consistent with these data. The Logan event, where partial containment was obtained, shows that an appreciable fraction of energy remains at a relatively lower temperature. Figure 12 shows the comparison between the calculated and observed energy deposition in a salt medium.

Venting was observed from the Gnome event (Fig. 13) within 7 minutes after detonation.[12] The gray smoke and steam emanating from the shaft may have carried away as much as 10 percent of the energy released. This figure is estimated from the total energy remaining at late times.

In the comparison of the salt and tuff data, it is significant that both media contain relatively high water concentrations. Therefore, these media rapidly approached the boiling point of water as the maximum temperature that can be expected to exist.

In Fig. 14 are shown the results of two shots in granodiorite, Shoal[11] and Hardhat.[16] We note that in the case of Hardhat, where appreciable quantities of water were artificially introduced during postshot drilling into a normally dry environment, the maximum temperatures achieved are limited because of the boiling point of water.

An apparent error in the integration of the residual energy in the Rainier event, as reported by Olsen *et al.*,[7,10] has led to the erroneous conclusion that a maximum of only one-half the energy released by an underground nuclear detonation remains as residual thermal energy. The results of the work reported in this paper show that 90 to 95 percent of the nuclear energy release remains as residual thermal energy if complete containment is achieved. These results are in essential agreement with the values predicted for very early times by the computer codes.

Correlation of the energy deposition with radial distance from the shot point is difficult because of the asymmetries in the temperature profiles. Table III summarizes the radial data derived from the temperature profiles shown in Figs. 3 to 8.

In general, it appears that at late times ambient temperatures exist at distances equivalent to a cavity diameter below the original shot point.

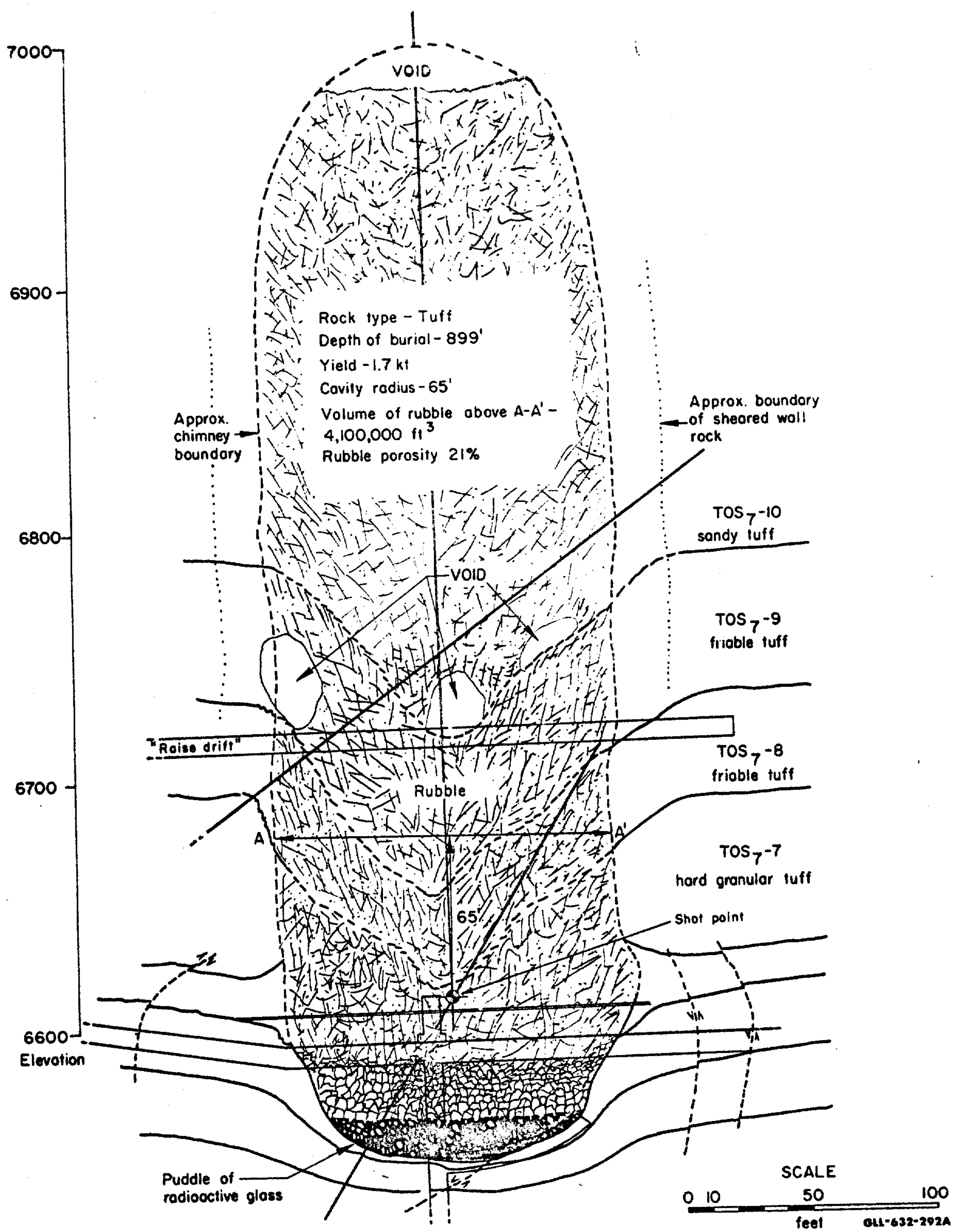

Fig. 12. Rainier schematic cross section.

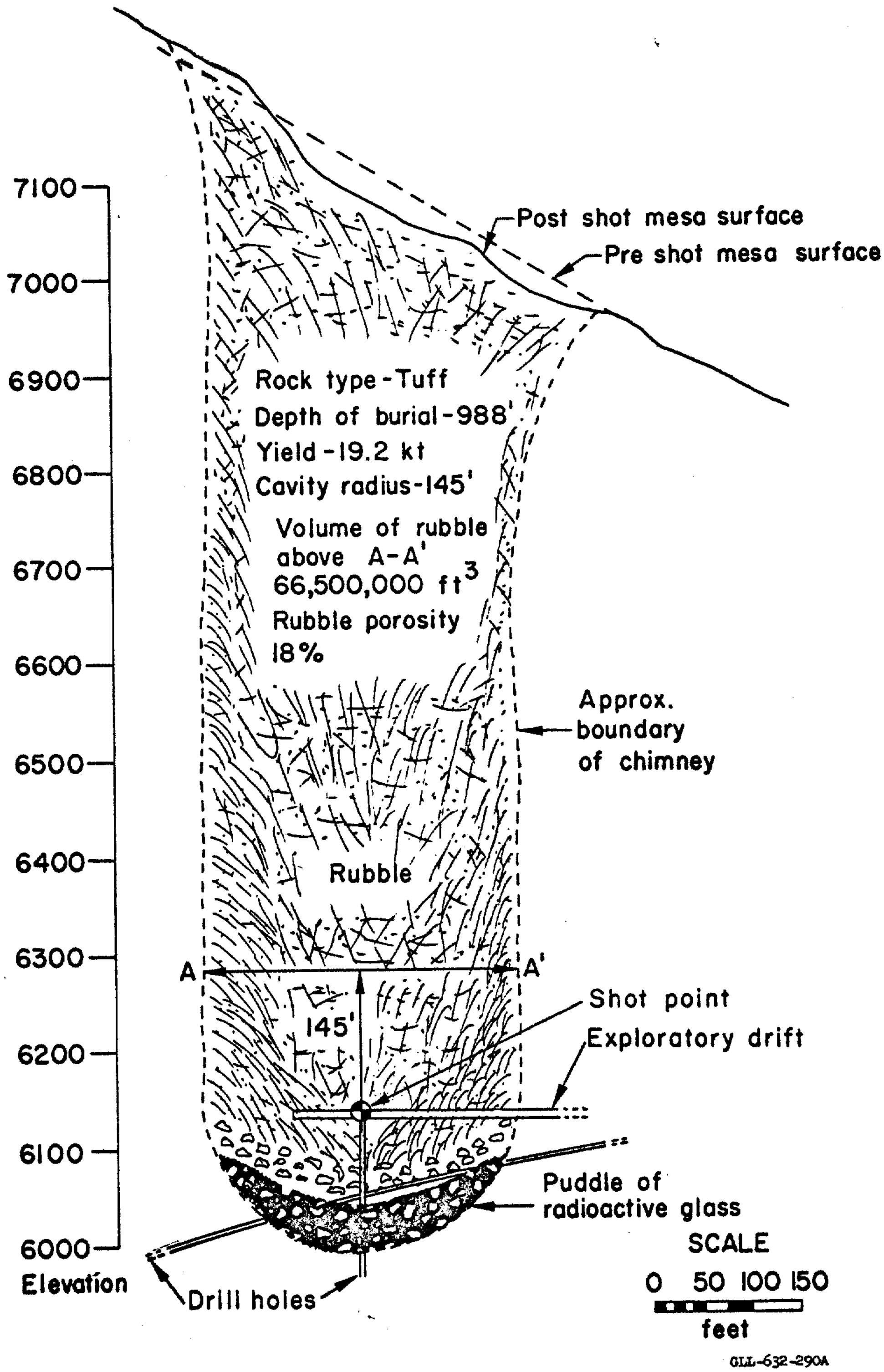

Fig. 13. Blanca schematic cross section.

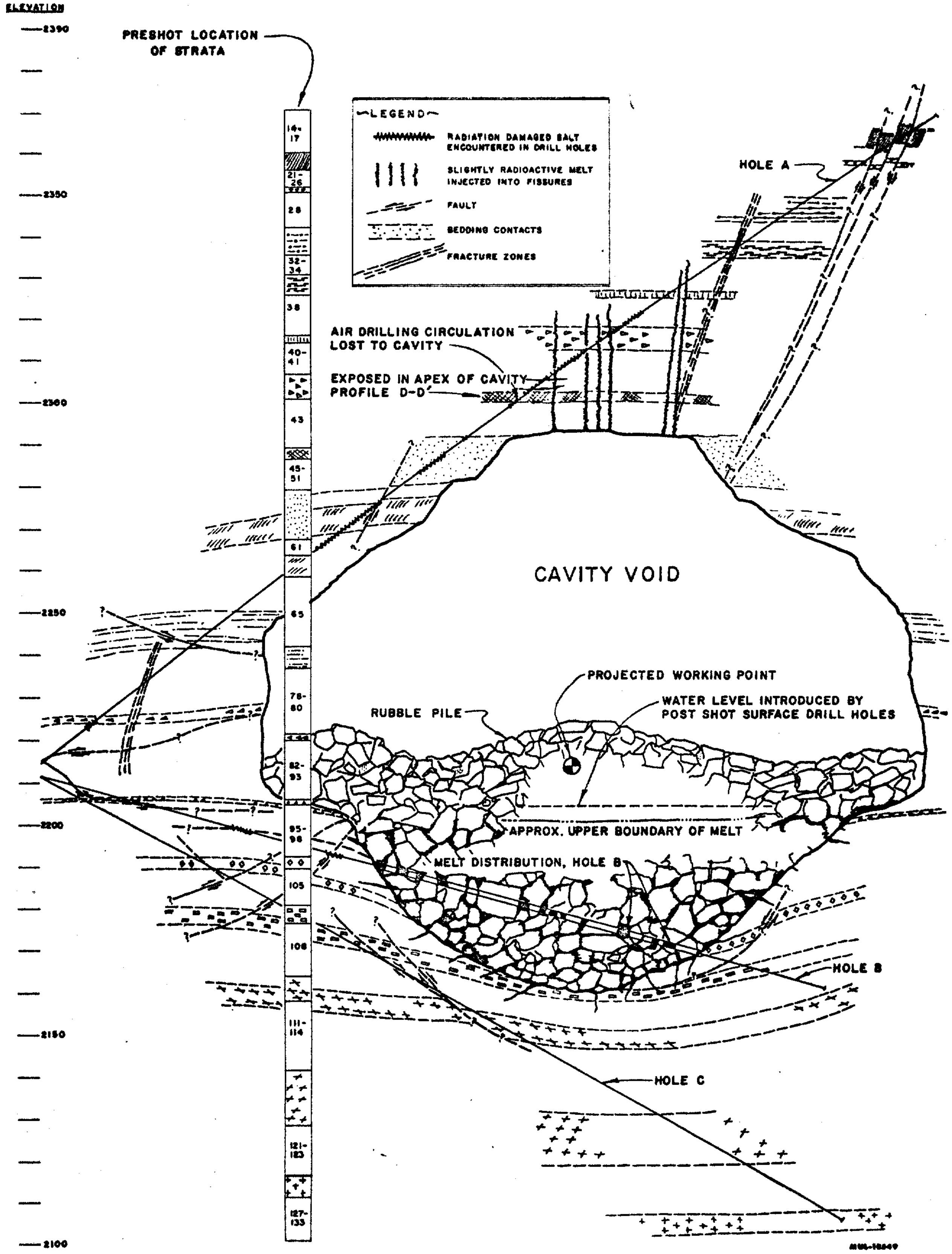

Fig. 14. Gnome cavity profile.

Table III. Radial energy distribution at late times.

Event	Media	Radial distance to ambient media temp. Fractional cavity radius
Gnome	salt	2.68
Rainier	tuff	1.69
Logan	tuff	1.41 - 1.96
Blanca	tuff	1.21 - 1.93
Shoal	granodiorite	1.72

From the temperature profiles and the energy distribution curves presented earlier, it is important to note that an appreciable fraction of the residual thermal energy exists in a large volume of material at very low temperature increases above ambient. In the case of Rainier, 50 percent of the energy release is contained in material within a 4°C rise above ambient.

CONCLUSIONS

In summary, the work presented in this paper shows that the analysis of the distribution of residual thermal energy at late times. i. e., a few months after detonation, is consistent with the energy distribution predicted by current computer codes for very early times, i. e., fractions of a second after detonation.

The actual fraction of residual energy that might be expected within a given isotherm in any detonation medium is most strongly influenced by the degree of containment of the nuclear explosion that is achieved. As would be expected from first principals, the thermodynamic quality of the residual heat energy is directly proportional to the amount of water present in the postshot environment. In experience to date, the water has come from one of three sources: artificially induced, e. g., by postshot drilling; the natural water table; or chemical water found in the minerals of the medium.

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